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REPORT NO. 573

THE LOAD-ENDURANCE RELATIONSHIP FOR A STATIC MANUAL RESPONSE

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ABSTRACT

THE LOAD-ENDURANCE RELATIONSHIP FOR A STATIC MANUAL RESPONSE

OBJECT

To determine the relationship between relative (percentage-of-maximum) muscle loading and the endurance of a manual response, and to study the effect of two body positions yielding different response strengths on endurance at identical relative loads.

RESULTS AND CONCLUSIONS

An essentially linear relationship was obtained between the relative load (percentage-of-maximum strength) and the endurance of the manual response within the range of relative loads employed. As the load was increased from 50% to 80% of maximum strength mean endurance decreased from 63.3 sec to 21.4 sec.

A comparison of the endurance scores for the two arm positions revealed very little difference in performance despite the fact that the mean absolute load (the actual force in pounds) was 41% greater at the 150° elbow angle than at the 80° angle. Thus, relative loading tended to equalize endurance despite large differences in the actual force of the sustained response.

Force x endurance (the response force multiplied by endurance) was significantly better at the 150° arm angle than at the 80° angle.

While stature, weight, and the arm dimensions were related to strength, they were not so clearly related to endurance. At the optimum elbow angle (150°) there was no statistically significant correlation between the body measurements and endurance.

RECOMMENDATIONS

The load-endurance function used in conjunction with appropriate strength norms may be used to predict the limits of endurance for a range of absolute loads. It would be highly desirable to extend the

range of relative loads beyond the limits used in this study in order to obtain a more general load-endurance function, and to compare the functions of diverse subject populations.

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THE LOAD-ENDURANCE RELATIONSHIP
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I. INTRODUCTION

Scientific concern with the measurement of human strength is by no means of recent origin. According to Hunsicker and Donnelly (1955), the first such study was reported by De La Hire in 1699. Since that time, several types of dynamometers have been developed to measure strength. In its usual application, the dynamometer is used either to measure the maximum strength of a muscle response, or the external force required to move a body member fixated by maximum voluntary effort. In recent years, work in this area has been expanded to include the study of endurance and the strength-endurance relationship. Typical of this more recent approach is the work of Elbel (1949) who studied the endurance of the leg as a function of the force applied to a pedal, and that of Tuttle, Janney, and Thompson (1950) who measured the relationship between initial maximum grip strength and strength-endurance for a fixed period of time. Rohmert (1960) measured response endurance at various fractions of the maximum response strength for different muscle groups. He found that for a given relative load (percentage-of-maximum strength) endurance was independent of the muscle group, and of the force of the response. In addition, he found that despite gross individual differences in maximum strength relative loading eliminated differences in endurance.

The primary purpose of the present study was to explore further the relationship between the load placed on a muscle group and the endurance of a static manual response. The response was analyzed both in terms of the proportionate relationship of the sustained force to the maximum strength of the response (the relative load) and an index of working efficiency, the actual control force times the time it was maintained.

II. METHODS AND PROCEDURE

Apparatus. The dynamometer equipment is shown in Figure 1. The basic apparatus consisted of an isometric dynamometer handle, an adjustable seat and footrest assembly, and a subject display. The handle was connected by a ball-and-socket joint to a bar of tool steel. Four strain gages wired as a Wheatstone bridge were cemented to a bar just under the handle. The gages formed the balanced input circuit of a strain amplifier. Pressure applied to the handle unbalanced the bridge circuit and a current proportional to the change in resistance of the gages was fed into the amplifier. The output of the amplifier drove one channel of a dual channel ink-writing oscillograph. The dynamometer handle was calibrated using a series of weights from 20 to 200 lb, a calibration curve was constructed, and a conversion table was made so that the pen deflections could be readily converted into pounds of applied force.

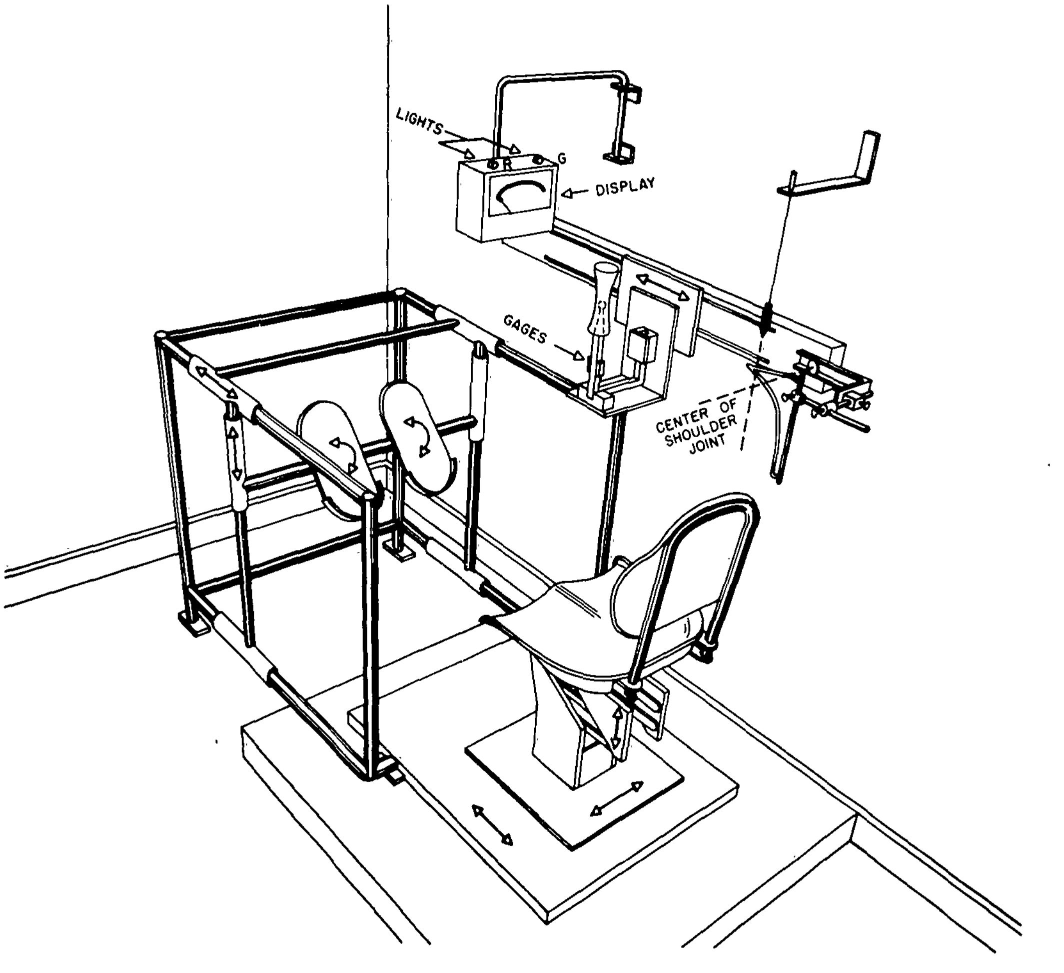

Fig. 1. Diagram of apparatus.

The subject display was a voltmeter connected in parallel with the oscillograph, the scale of which was marked in pounds of force. An amplifier connected to the display meter energized a bipolar relay which controlled a red and a green light. A bias control on the relay amplifier permitted adjustment of the switching point of the relay so that the green light would turn on, and the red light off, at any desired meter reading--that is, at a given force on the handle. Thus, whenever the force applied to the handle was below the desired value the red light was on, and when the force equalled or exceeded the preset value, the green light was on. This made it possible to set a goal output for the subject by the simple instruction to keep the green light on as long as possible. This supplementary display was necessary because a subject nearing the limit of endurance has difficulty in attending to the voltmeter needle. Whenever the green light of the display was on, a 60 cycle voltage was delivered to the second channel of the recorder. The duration of the AC signal on the oscillograph provided a record of the time for which the force applied to the handle equalled or exceeded the goal value.

The seat was provided with vertical and fore-and-aft adjustments which made it possible to place all subjects, regardless of size, in the same anatomical position. The seat height was adjusted to place the approximate center of the glenohumeral joint at the level of the center of the handle. Also, the seat was adjusted to align the center of the shoulder joint with the zero point of the scale by which the handle position was determined.

The footrests were 6 in. x 12 in. steel plates which were free to rotate about a horizontal shaft. The distance between the centers of the footrests was 14 in. The free rotation of the plates required the subject to select a footrest angle at which pressure could be applied without subjecting the ankle to torsional strain.

Subjects. Sixty-four male college students were employed in this investigation. All were volunteers recruited without respect to strength or body type. Some of the physical characteristics of the subjects are shown in Table 1. These particular arm characteristics were chosen because Roberts, Provins, and Morton (1959) have shown that they are related to the strength of elbow flexion and extension. The mean age of the subjects was 19.9 years with a standard deviation of 2.4 years.

Procedure. Prior to the experiment, the physical measurements were made on each subject and the necessary seat, footrest, and handle positions were determined.

TABLE 1

MEANS AND STANDARD DEVIATIONS OF MEASUREMENTS ON ALL SUBJECTS WITH DESCRIPTION OF MEASUREMENTS

(N = 64)

	Measurement	Mean	S. D.
1.	Weight	159.9 lb	25.8 lb
2.	Stature	69.6 in.	2.3 in.
3.	Upper arm length	13.1 in.	0.7 in.
4.	Upper arm girth	11.6 in.	1.2 in.
5.	Forearm length	10.3 in.	0.6 in.
6.	Forearm girth	10.8 in.	0.9 in.

1. Nude weight as measured by platform spring balance.
2. Height to vertex. Subject standing comfortably erect with eyes focused horizontally forward.
3. From acromion to upper margin of head of radius with the arm hanging loosely at the side.
4. Midway between the acromion and upper margin of head of radius with muscles relaxed and arm hanging loosely at the side.
5. From upper margin of head of radius to tip of styloid process of radius.
6. Maximum girth with muscles relaxed and arm hanging loosely at the side.

The body attitude was the same for all subjects. The seat was positioned, and the footrest was set by the experimenter to place the long axis of the thigh at an angle 20° above the horizontal and to produce an angle of 150° between the long axes of the thigh and lower leg. Also, the two handle positions required to produce elbow-angles of 80° and 150° were determined for each subject.

For two sessions prior to actual testing, the subjects were given instructions and practice in both the strength and endurance tests. In the four strength tests given in each of the two practice sessions, the subject was instructed to pull as hard as possible on the handle for 7 sec and to attain his maximum output in about 1 sec. These instructions were given to suppress the tendency to "slam" the handle. In the endurance tests given in the practice sessions, the display amplifier was set to turn on the green light at a value one-half the subject's maximum strength for each arm position and he was instructed to pull just hard enough to turn the green light on and to keep it on as long as possible. The trial was terminated by the experimenter if the subject's output fell below the required level and he was unable to turn the green light on again within 3 sec. The endurance measure was the length of time the subject was able to maintain the required output. This was determined by measuring the length of the line on the recording paper which indicated the operation of the green light.

In the study proper, the endurance of horizontal pull was measured for each subject at 50%, 60%, 70%, and 80% of his maximum pull at both the 80° and the 150° elbow-angle. An 8 x 8 Latin Square design was used so that with 64 subjects each experimental condition was experienced by 8 subjects at each order of presentation.

The dynamometer handle was set to produce two extreme elbow-angles (80° and 150°) in order to vary the mechanical advantage of the arm complex. Previous work (Caldwell, 1960) has shown that the maximum strength of a manual pull is dependent upon the elbow-angle. Thus, with the use of the relative loading technique, in which each subject was loaded to given proportions of his maximum strength for each position, the actual forces maintained were quite different at the two arm positions.

Each subject received two trials a day for 4 experimental days. The two trials on a given day were separated by a 20 min rest period, and the sessions were minimally 24 hr apart.

III. RESULTS AND DISCUSSION

Strength. The mean strength of horizontal manual pull at the 80° elbow-angle was 114.6 lb with a standard deviation of 17.9 lb. The range in strength was from 79 to 190 lb. At the 150° elbow-angle, the mean strength was 162.0 lb with a standard deviation of 26.0 lb, and the range was from 117 to 238 lb. Thus, as has been previously noted in heterogeneous samples, the strongest subject was approximately twice as strong as the weakest. These strength means are considerably greater than those reported by Hunsicker (1955), though the two samples were practically identical in age, stature, and weight. The difference in strength measures is most likely due to better conditions of body stabilization in the present study.

Strength is not a fixed attribute, but varies with such factors as body attitude and the degree of body stabilization. Thus, a subject has as many "strengths" as there are different conditions of measurement, and individuals can be compared in strength only when measured under uniform conditions. (In this paper, the term "strength" is used only when referring to the maximal response, and "force" is employed when referring to a sub-maximal response.)

A comparison of strength and weight revealed that at the lesser (80°) elbow-angle the subjects pulled 73% of their body weight with a standard deviation of 11%, while at the greater elbow-angle they pulled 103% of their body weight with a standard deviation of 17%. Thus, it may be stated that at the most favorable arm position, and with good body stabilization, men on the average should exert a manual pull approximately equal to their body weight. Two-thirds of the strength measures should be between about 86% and 120% of body weight.

Endurance. The main results of the experiment are shown in Figure 2, and in the analysis of variance of these data given in Table 2. It is apparent in Figure 2 that with an increase in the relative load there was an essentially linear decrease in the duration of the response. These data are in close agreement with those reported by Rohmert, though the endurance scores are slightly greater in the present study. For example, Rohmert reported a mean endurance of 60.6 sec at a 50% load, whereas the present study yielded an endurance score of 63.3 sec. Comparable small differences were obtained at the other relative loads.

In the analysis of variance, the F-ratio for "Angles" indicates that there was a statistically significant different in mean endurance at the two arm positions. The mean endurance was 42.8 sec at the 80° elbow-angle and 39.5 sec at the 150° angle. Considering the statistical significance of the F-ratio for the "Angles x Subjects" interaction ($p < .01$), which indicates that an appreciable number of subjects had greater endurance at the 150° elbow-angle rather than at the 80° angle, little emphasis can be placed on the difference in endurance at the two arm angles.

A second method for assessing the effect of load on endurance involves the relating of individual differences in strength to differences in endurance. Since the forces to be maintained by each subject were proportions of his strength, there were large differences in the physical loads imposed on the subjects.

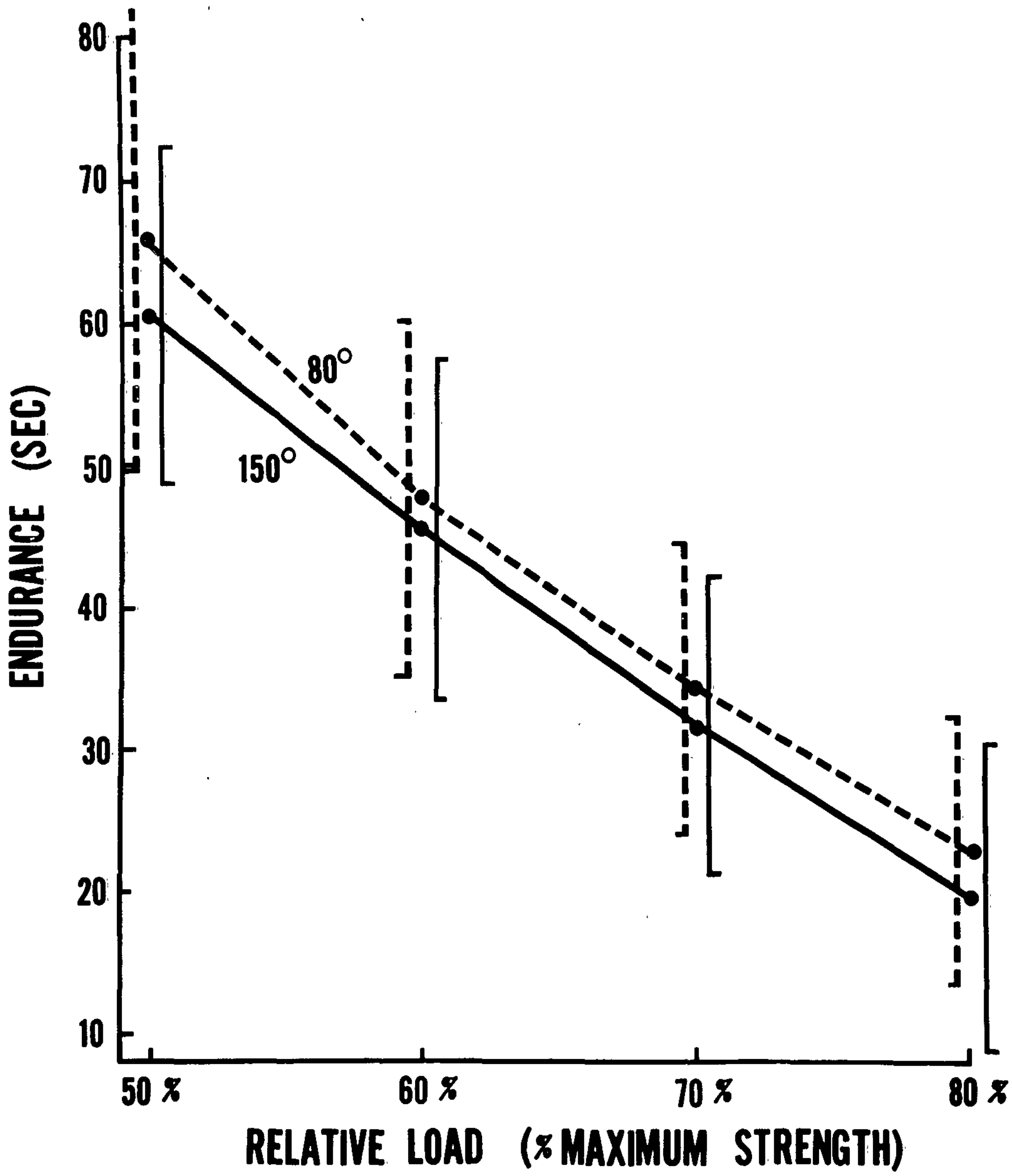

Fig. 2. Mean endurance of sustained response at four relative (percentage-of-maximum) loads at two arm positions with standard deviations for each set of measures.

TABLE 2

ANALYSIS OF VARIANCE OF ENDURANCE SCORES AT FOUR RELATIVE LOADS AT TWO JOINT ANGLES

	Source	df	MS	F
1.	Loads (L)	3	41,656.14	682.78**
2.	Angles (A)	1	1,363.39	6.87*
3.	Subjects (S)	63	622.66	6.53**
4.	L x A	3	65.48	1.22
5.	A x S	63	198.45	3.69**
6.	L x S	189	61.01	1.14
7.	L x A x S	189	53.74	
	Total	511		

*$p < .05$

**$p < .01$

In the analysis of variance, the F-ratio for "Subjects" was significant at the 1% level of confidence. This variation in individual endurance, however, cannot be attributed to differences in strength since none of the correlations between strength and endurance at the various relative loads approached statistical significance. For example, the correlations of the strengths of the 64 subjects at the 150° elbow-angle with the endurance measures at the four relative loads were calculated and the following values were obtained: -.08, -.03, -.09, and -.04. Apparently, the relative loading technique compensated for individual differences in strength sufficiently so that for any relative load there was no relationship between strength and endurance. Thus, the significant F-ratio for "Subjects" indicates that the individual differences in endurance must be related to some factor or factors such as motivation, physical conditioning, or some other as yet unidentified characteristic.

Tuttle *et al* reported a negative correlation between maximum grip strength and the percentage of grip strength maintained for 1 min. They concluded that (with the instruction to exert as much force as possible during the period of measurement) weaker individuals can maintain a greater proportion of their maximum strength than can stronger ones. Since no such relationship was obtained in the present study with the output level constant and proportional to the subject's strength, it may mean that when subjects are free to vary the force of a continuing response the stronger subjects tend to assume greater relative loads at the beginning than do the weaker ones, and thus fatigue themselves at a disproportionately fast rate. This interpretation is supported by the lack of a one-to-one relationship between the relative load and endurance as shown in Figure 2, where it is apparent that a 30% increase in relative load resulted in a 66% decrease in endurance.

In order to examine the effect of extremes in strength on endurance, the strongest subjects (at least one S. D. above the mean strength of all subjects) were compared as a group with the weakest (at least one S. D. below mean strength). The endurance functions were almost identical for the two groups. The difference between the mean endurance for the two groups was 1.3 sec. (Each group contained 10 subjects.)

Force x Endurance. Since there was comparatively little difference between the endurance scores at the two elbow-angles, despite the fact that the mean control force at the 150° elbow-angle was 41% greater than at the 80° angle, the product of force and endurance was necessarily greatest at the larger elbow-angle. In the following analysis, the force maintained by each subject at each relative load for the two elbow-angles was multiplied by the endurance of the holding response to yield a "force x endurance" score. The mean force x endurance scores are shown in Figure 3, and the analysis of variance of these data is given in Table 3. The statistically significant F-ratio for "Angles" ($p < .001$) shows a clear separation between the means for the two arm positions. The mean force x endurance score was 2970 at the 80° angle and 3870 at the 150° angle. Thus, mean force x endurance was 30% greater at the 150° position than at the 80° position. The F-ratio for "Angles x Subjects" ($p < .001$) shows, however, that the superiority of the 150° position was not uniform for all subjects. Nevertheless, only 8 of the 64 subjects showed this reverse effect.

The highly significant F-ratio for "Loads" indicates that the decrease in endurance with an increase in applied force was not fully compensatory. An increase in force caused a disproportionately large decrease in endurance. It is evident from the significant "Angles x Load" interaction that the effect of force on endurance was different at the two arm positions. As shown in Figure 3, the curves for the two elbow-angles converge as the response force increases, thus indicating a reduction in superiority of the 150° position over the 80° position with an increase in load.

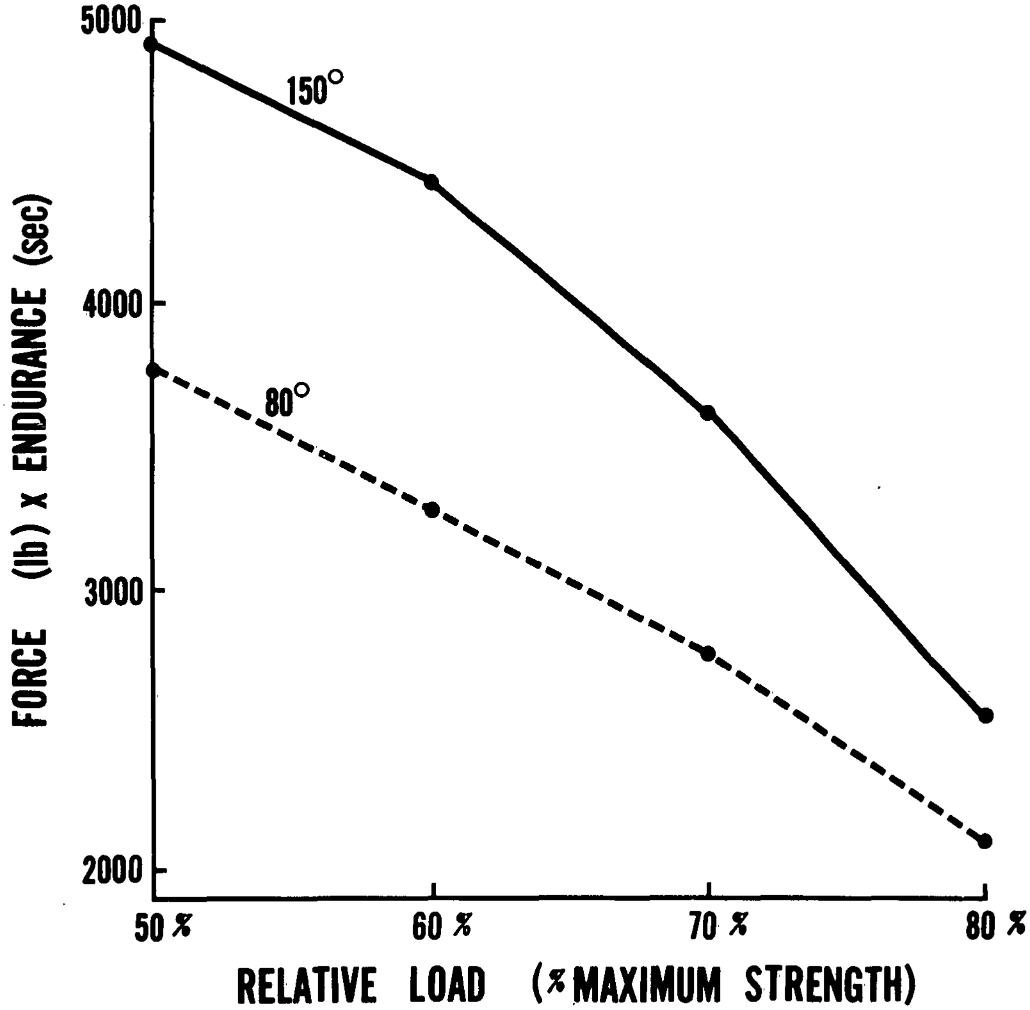

Fig. 3. Mean force x endurance at four relative loads for the two arm positions.

TABLE 3

ANALYSIS OF VARIANCE OF THE FORCE x ENDURANCE SCORES AT FOUR RELATIVE LOADS AT TWO JOINT ANGLES

Source	df	MS	F
1. Angles (A)	1	10,347.5	72.11**
2. Loads (L)	3	9,694.3	198.25**
3. Subjects (S)	63	668.7	4.66**
4. A x L	3	351.9	7.91**
5. A x S	63	143.5	3.22**
6. L x S	189	48.9	1.10
7. A x L x S	189	44.5	
Total	511		

**$p < .001$

Body Size as Related to Strength and Endurance. The subjects employed in this study can be compared with those of Roberts *et al* on the measures listed in Table 1. The subjects in the present study were taller by 1.38 in. and heavier by 13.36 lb than those employed by Roberts *et al*. Consistent with these differences, it was noted that there were small differences in upper arm and forearm lengths, but comparatively large differences in the two measures of arm girth. Thus, there were small differences in the longitudinal measurements of the two samples, but rather large differences in weight and in the girth measurements. The present group was more comparable to the U. S. Air Force flying personnel measured by Hertzburg, Daniels, and Churchill (1954). The Air Force personnel were 0.47 in. shorter and 3.78 lb heavier on the average than those in the present study.

The correlations between six body measurements and two measures of elbow strength obtained by Roberts *et al* are shown in Table 4. Also shown are the correlations between the body measurements and the two measures of strength obtained in the present study. The two sets of correlations are fairly comparable despite the difference in the two techniques of strength measurement. The correlations between the body measurements and strength, as Roberts *et al* stated, suggest that people who are above average in one body dimension tend to be above average in all dimensions and in limb strength.

TABLE 4

PRODUCT-MOMENT CORRELATIONS BETWEEN BODY MEASUREMENTS AND THE STRENGTH MEASUREMENTS OF ROBERTS et al AND CALDWELL

Measurement	Roberts et al (N = 41) Flexion Strength	Roberts et al (N = 41) Extension Strength	Caldwell (N = 64) Strength 80°	Caldwell (N = 64) Strength 150°
Stature	.45*	.44*	.57**	.50**
Weight	.47*	.68**	.46**	.40*
Upper arm length	.34	.41*	.28	.21
Forearm length	.47*	.21	.38*	.51**
Upper arm girth	.40*	.44*	.31*	.32*
Forearm girth	.64**	.70**	.37*	.43**

*$p < .01$
**$p < .001$

The next question to be considered is whether body size is related to endurance when individual differences in strength are compensated for by means of the relative loading technique. The correlations between the body measurements and endurance are shown in Table 5. It is apparent that at the 150° elbow-angle variations in the body measurements were unrelated to variations in endurance. At the 80° position, however, three measures were significantly correlated with endurance. The correlation between weight and endurance may be related to the apparent tendency of many subjects to fixate the arm and to hang from the handle at the lesser elbow-angle, and thus to utilize body dead weight to augment the muscle action. The correlation of the arm girth measurements with endurance at the 80° angle, but not at 150°, suggests that the greater mechanical disadvantage of the system at the lesser elbow-angle had a greater effect upon endurance than upon strength.

TABLE 5

PRODUCT-MOMENT CORRELATIONS BETWEEN BODY MEASUREMENTS AND ENDURANCE AT TWO ELBOW-ANGLES

Measurement	Endurance in Seconds 80°	150°
Stature	.02	-.01
Weight	.32*	.07
Upper arm length	.02	-.04
Forearm length	.15	.07
Upper arm girth	.32*	.06
Forearm girth	.45**	.13

*$p < .01$

**$p < .0005$

IV. SUMMARY

The maximum strength of manual pull was determined for 64 male college students at two arm positions known to yield different mean strengths. Each subject was then required to maintain 50%, 60%, 70%, and 80% of his own maximum strength at the two arm positions as long as possible. The main results of the study were as follows:

1. The mean strength of manual pull was 114.6 lb at the 80° elbow-angle, and 162.0 lb at the 150° angle. At the arm position which yielded the greatest response strength the subjects pulled an average of 103% of their body weight. Two-thirds of the subjects pulled between 86% and 120% of their body weight.

2. An essentially linear relationship was obtained between the relative load and the endurance of the response within the range of relative loads employed. As the load was increased from 50% to 80% of maximum strength mean endurance decreased from 63.3 to 21.4 sec.

3. Force x endurance (the response force multiplied by endurance) was much better at the 150° angle than at the 80° angle. The influence of arm position, or the control force, on the force x endurance scores decreased with an increase in load.

4. While stature, weight, and the arm dimensions were related to strength, they were not so clearly related to endurance. At the optimal elbow-angle (150°) there were no statistically significant correlations between the aforementioned body measurements and endurance. Thus, when differences in strength were removed by use of relative loading, endurance was apparently unrelated to body size.

5. With the use of relative loading, individual differences in endurance were unrelated to differences in strength. That is, relative loading apparently compensated for gross differences in strength sufficiently that the residual subject differences may be relatable to such factors as motivation or physical conditioning.

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